# Massive Gas Jets Interaction with Magnetic Confined Plasma

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# Outline

a. Introduction
  - Plasma definition and basic magnetic confinement concepts
  - Tokamak
  - Plasma major instabilities and Disruptions

b. Gas behaviour in vacuum
  - Jet flow first expansion
  - Jet flow propagation into constant cross sectional duct
  - Some numerical results for H, He, Ne, Ar and Kr

c. Jet flow interaction with Plasma

d. Continuity equation

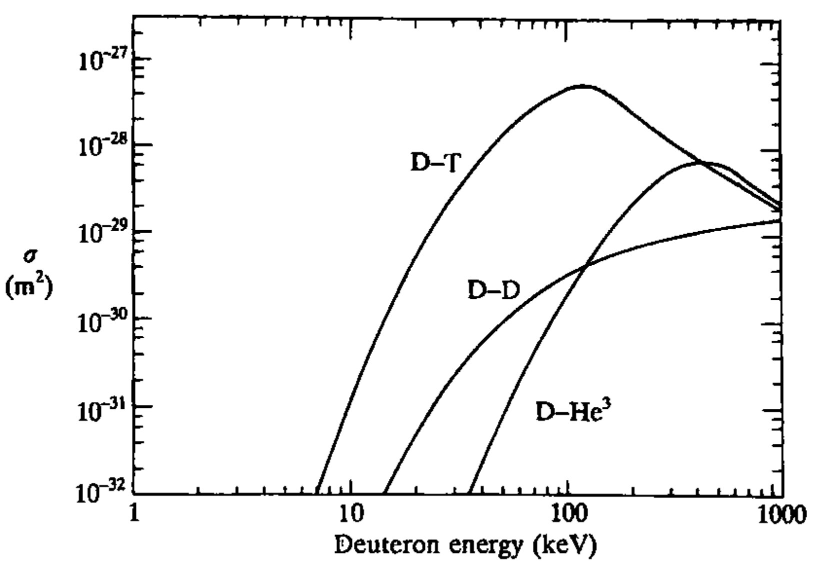
e. Electron heat balance equation

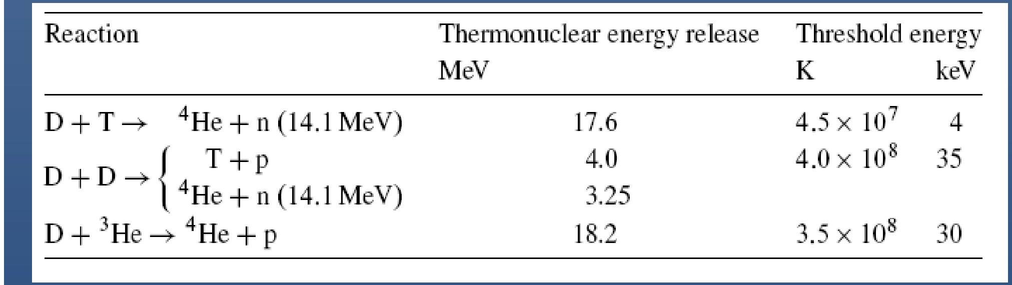
f. Future work: Ion energy balance equation

# Basic Plasma Concepts

- <u>Plasma:</u> an **ionized gas** characterized by electric neutrality in which at least one electron is stripped out of the atomic shell.

- (D,T) reaction is the best candidate for fusion energy production
- Maximum cross-section at *T* of 100 keV and minimum threshold energy of 4 keV





| Reaction | Thermonuclear energy release | Threshold energy | |
|---|---|---|---|
| | MeV | K | keV |
| $D + T \rightarrow {}^4He + n$ (14.1 MeV) | 17.6 | $4.5 \times 10^7$ | 4 |
| $D + D \rightarrow \begin{cases} T + p \\ {}^4He + n \text{ (14.1 MeV)} \end{cases}$ | 4.0<br>3.25 | $4.0 \times 10^8$ | 35 |
| $D + {}^3He \rightarrow {}^4He + p$ | 18.2 | $3.5 \times 10^8$ | 30 |

# Magnetic confinement

- Lawson criterion for confinement so that the output energy is at least equal to the input energy

$$n_e T_e \tau_e > 2.6 \times 10^{21}$$

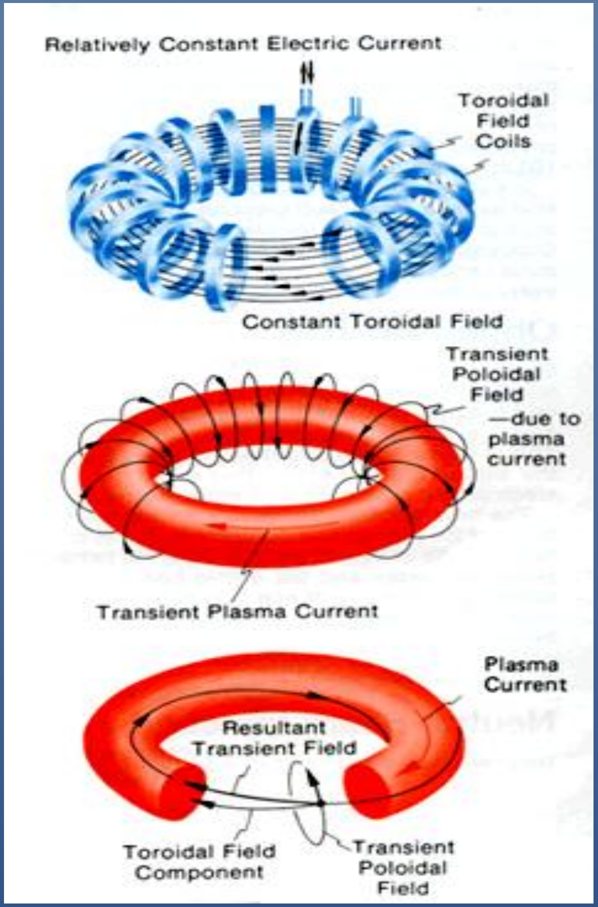
- Ways to increase the energy confinement time $\tau_E$

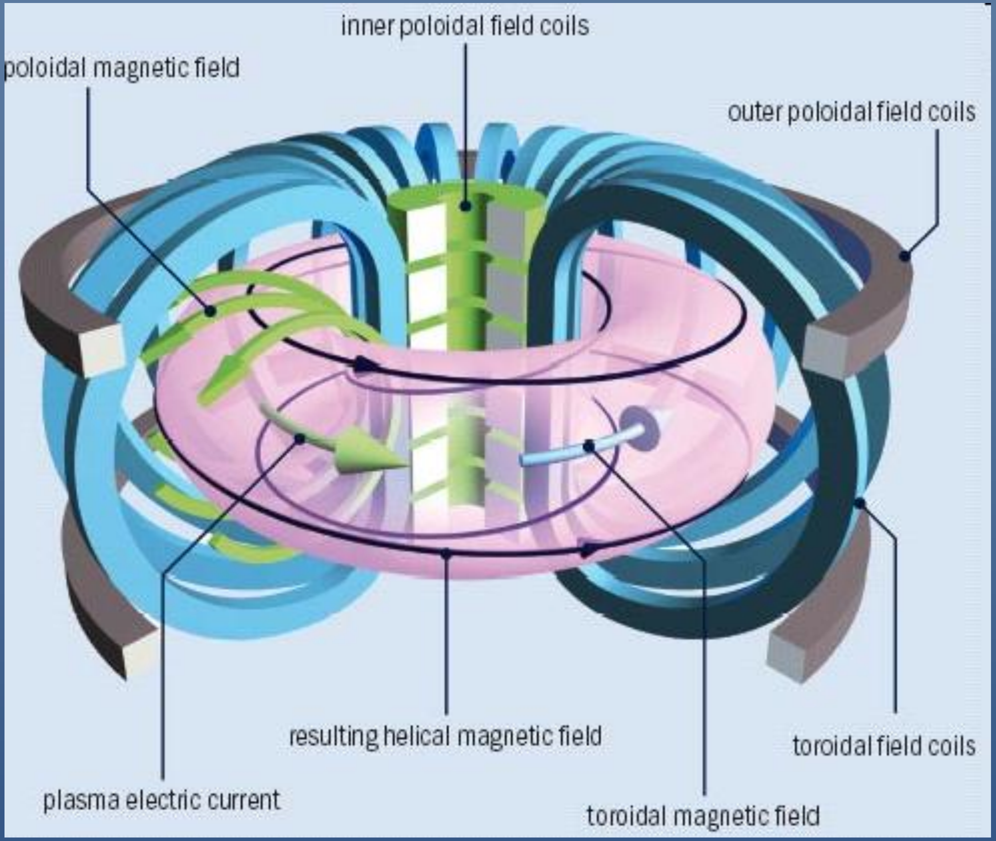
  **Magnetic confinement technique** relies on an external high magnetic field configuration (1-10 T) imposed on the plasma by a carefully chosen external geometry of the fusion device.

- Ways to increase the plasma temperature: →
  - Ohmic Heating
  - Wave Heating
  - NBI

- Ways to increase plasma density, gas puffing or/and NBI

# Tokamak

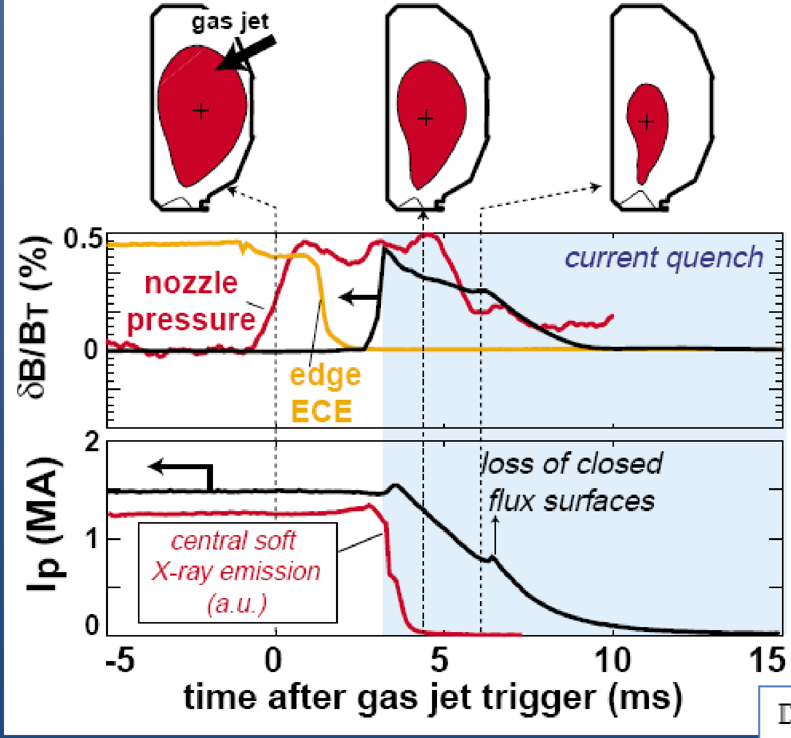


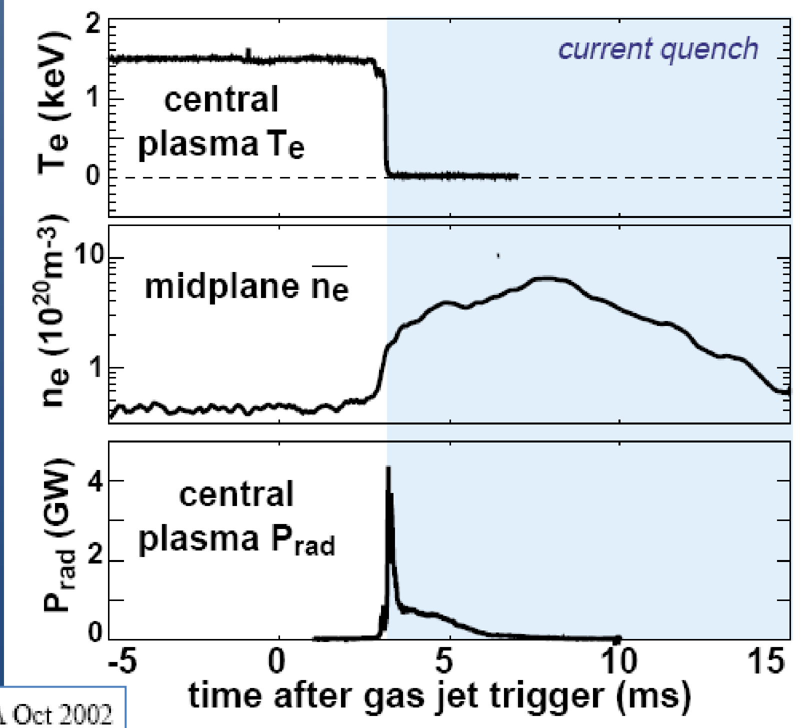


- Toroidal plasma confinement system characterized by both toroidal and poloidal magnetic fields $B_\varphi$ and $B_\theta$.
- $B_\varphi$ is induced by currents passing through coils surrounding the plasma
- $B_\theta$ is induced by the plasma current itself.

# Disruptions Instabilities in tokamaks

- Disruptions are mainly caused by: (1), high electron density, (2) high pressure values and (3), lack of position control inside the tokamak.
- As a result, we have, (1), complete loss of plasma confinement, (2), rapid temperature decrease, (3), plasma current decay and (4), possible development of runaway electrons.
- **ALL OF THESE EFFECTS CAUSE TREMENDOUS STRESS ON THE VESSEL**





D.G. Whyte, IAEA Oct 2002

# Disruption Mitigation

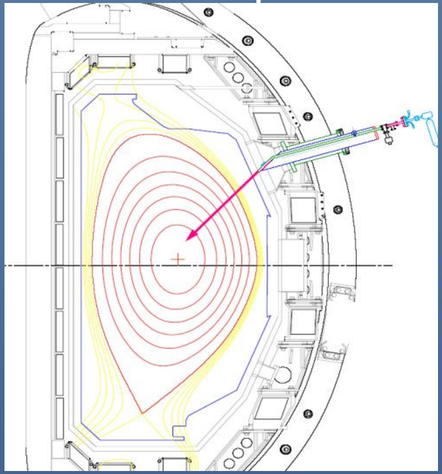
- Massive Gas puffing is one solution for the disruption mitigation
- Each injected gas atom collides with a charged particle and is ionized
- As a result, an increase in the electron density but a reduction in the energy as 13.6 eV is lost per ionization.

- **This decreases the electron temperature and allows a controlled shot-down of the plasma without major heat load on the vacuum chamber.**

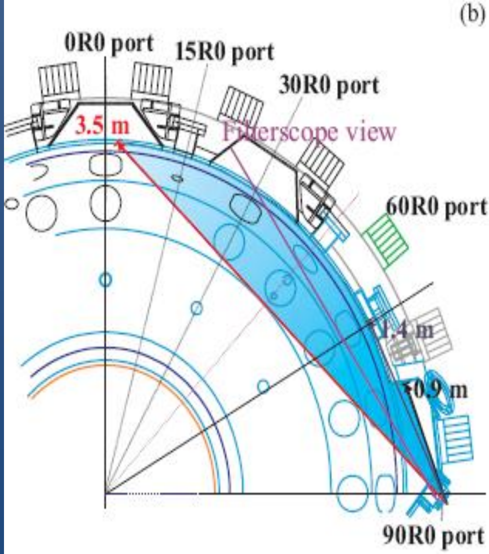
- **OUR GOALS ARE:**
  - **Describe the gas jet behaviour in free expansion or in ducts**
  - **Describe the gas jet interaction with the plasma**
  - **Build a numerical code to include all the processes**
  - **Predict the feasibility of this method for present and future fusion devices.**

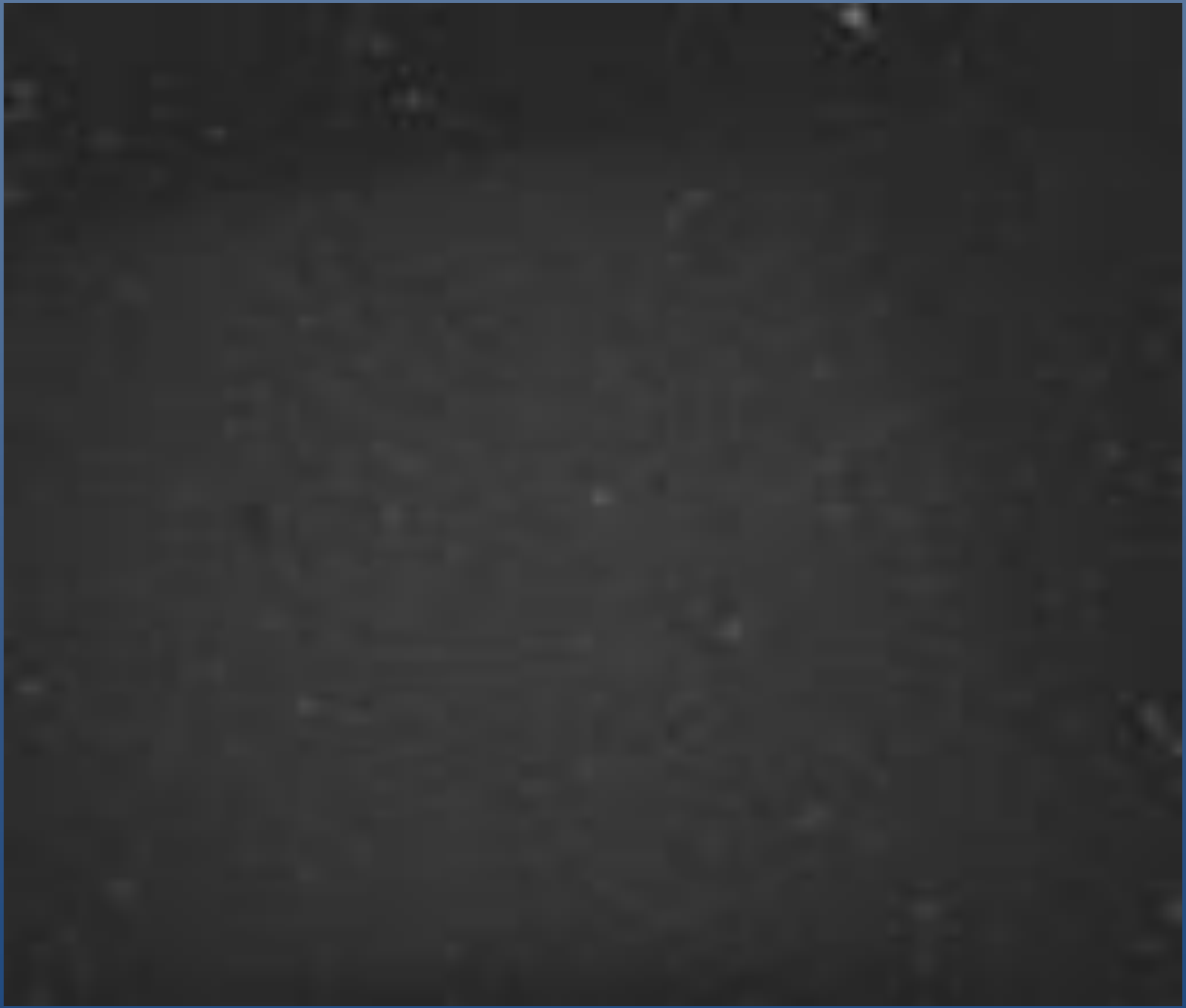
# Massive gas jet disruption mitigation viewed with a fast imaging camera (1 μs exposure time and 15 μs between frames)

Poloidal plane

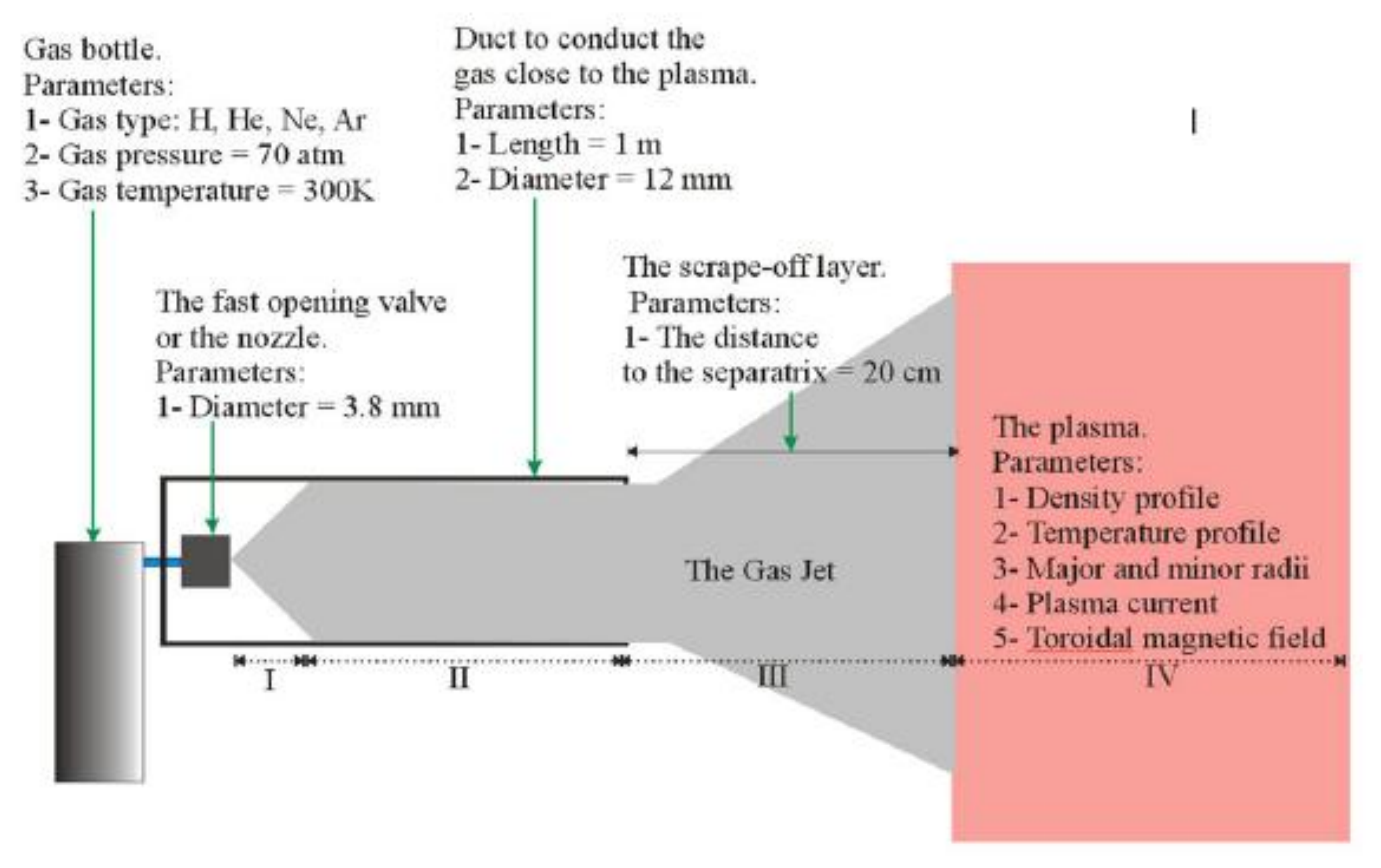


Toroidal plane





# Gas jet behaviour in Vacuum and ducts



Gas bottle.
Parameters:
1- Gas type: H, He, Ne, Ar
2- Gas pressure = 70 atm
3- Gas temperature = 300K

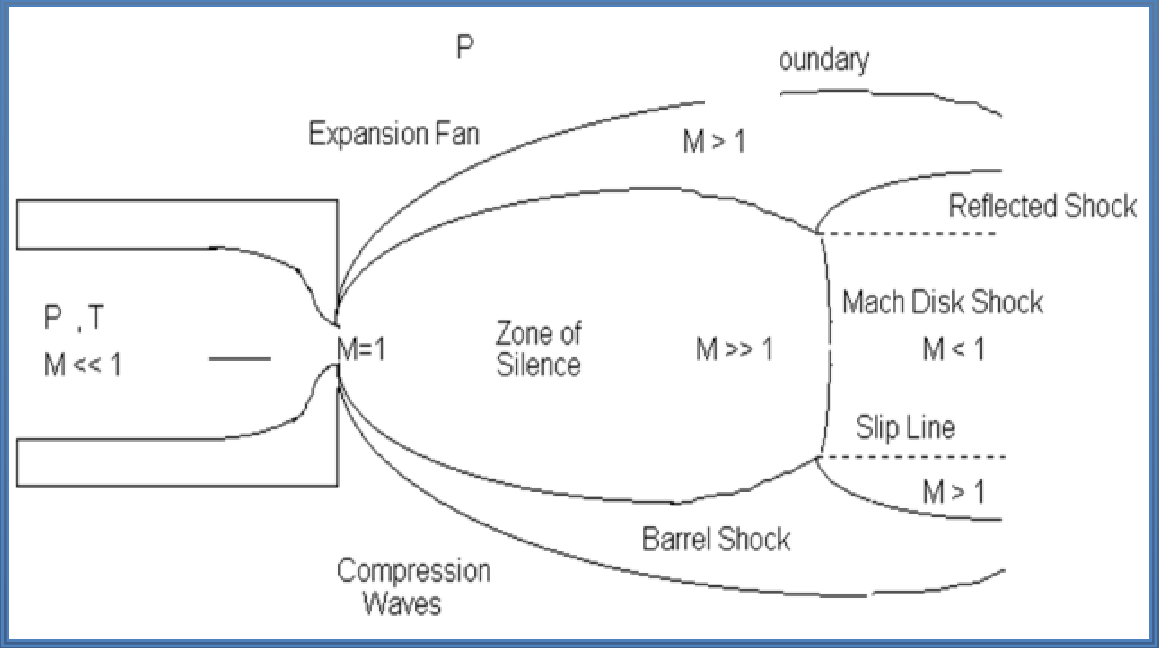
Duct to conduct the gas close to the plasma.
Parameters:
1- Length = 1 m
2- Diameter = 12 mm

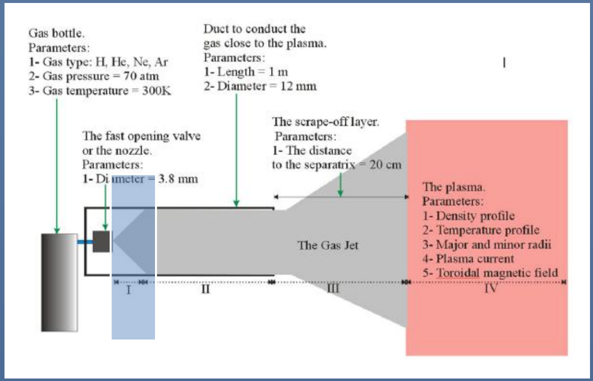
The fast opening valve or the nozzle.
Parameters:
1- Diameter = 3.8 mm

The scrape-off layer.
Parameters:
1- The distance to the separatrix = 20 cm

The plasma.
Parameters:
1- Density profile
2- Temperature profile
3- Major and minor radii
4- Plasma current
5- Toroidal magnetic field

# Gas Jet Free Expansion (Phase I)





$$G = ((\gamma + 1)/2)^{\frac{\gamma}{\gamma-1}}$$

- The flow jet exists from the nozzle at $M = 1$:
  - If $P_0 / P_b < G$, the flow exists subsonically.
  - If not, it will exit supersonically, axial velocity increases till reaching

$$V_\infty = \sqrt{\frac{2R}{W}\left(\frac{\gamma}{\gamma - 1}\right)T_0}.$$

- Presence of shock waves in supersonic expansion
- During the expansion, temperature decreases leading to the sound speed decrease and thus the Mach number $M = V/c_s$ increase

# Physical Quantities put as a Function of *M*

- $PV^{\gamma}$ = Constant (adiabatic process)
- $P = (R/W)nT$ (ideal gas)

$$\frac{P_0}{P^\star} = (1 + \frac{\gamma-1}{2}M^2)^{-\frac{\gamma}{\gamma-1}} \quad ,$$

$$\frac{n_0}{n^\star} = (1 + \frac{\gamma-1}{2}M^2)^{-\frac{1}{\gamma-1}} \quad ,$$

$$\frac{T_0}{T^\star} = (1 + \frac{\gamma-1}{2}M^2)^{-1} \quad ,$$

$$\frac{A_0}{A^\star} = \frac{1}{M}(\frac{(\gamma+1)/2}{1+(\gamma-1)M^2/2})^{\frac{\gamma+1}{\gamma-1}} \quad .$$

- Once the variation of $M$ is determined, the evolution of $P_0$, $n_0$, $T_0$ and $A_0$ is obtained.
- $P^*$, $A^*$, $n^*$ and $T^*$ are the values of pressure, cross section, density and temperature corresponding to $M$=1.

# *M* as a Function of *Z* for Free Expanding Jet

- The Mach number behavior is obtained by **numerical simulation of the full Navier-Stokes Equation of a compressible flow** with the adequate numerical scheme that takes into account the presence of shock waves.
- A **polynomial fit** of the Mach number dependence on distance to the nozzle is determined and leads to:

$$
\begin{aligned}
M &= Z^{(\gamma-1)}\left(C_1 + \frac{C_2}{Z} + \frac{C_3}{Z^2} + \frac{C_4}{Z^3}\right) \quad \text{for } Z > 0.5, \\
M &= 1 + AZ^2 + BZ^3 \quad \text{for } 0 < Z < 0.5.
\end{aligned}
$$

| | $\gamma$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $A$ | $B$ |
|---|---|---|---|---|---|---|---|
| H | 1.4 | 3.606 | −1.742 | 0.9226 | −0.2069 | 3.19 | −1.61 |
| He, Ne, Ar and Kr | 1.6 | 3.232 | −0.7563 | 0.3937 | −0.0729 | 3.337 | −1.541 |

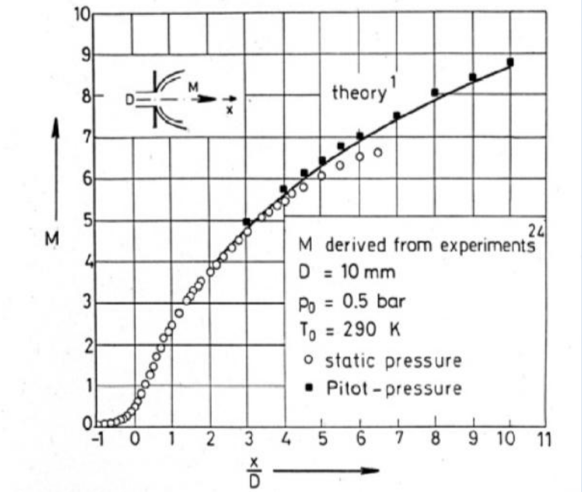
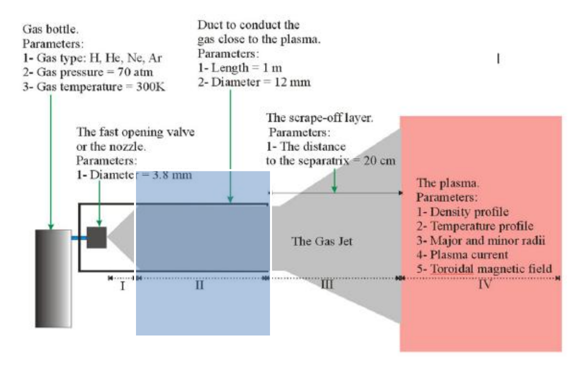


**Figure 2.** Sub- and transsonic free jet measurements: supersonic theory,[1] $\kappa = 1.40$.

G. Koppenwallner and C. Dankert, J. Phys. Chem., **91**, 2482 (1987)

# Jet propagation into constant cross-sectional duct (Phase II)

$$\frac{dM}{dx} = \frac{\gamma M^3}{2} \frac{1 + (\frac{\gamma - 1}{2}) M^2}{1 - M^2} \frac{4f}{D}$$

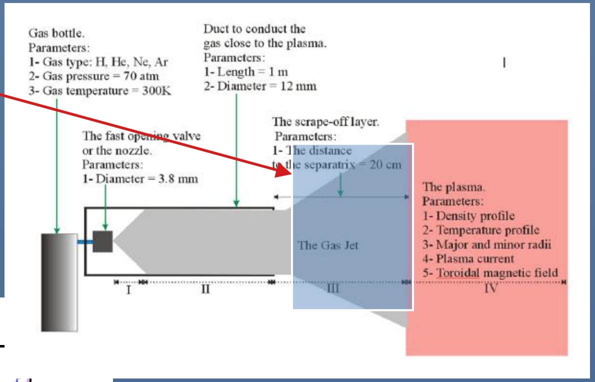


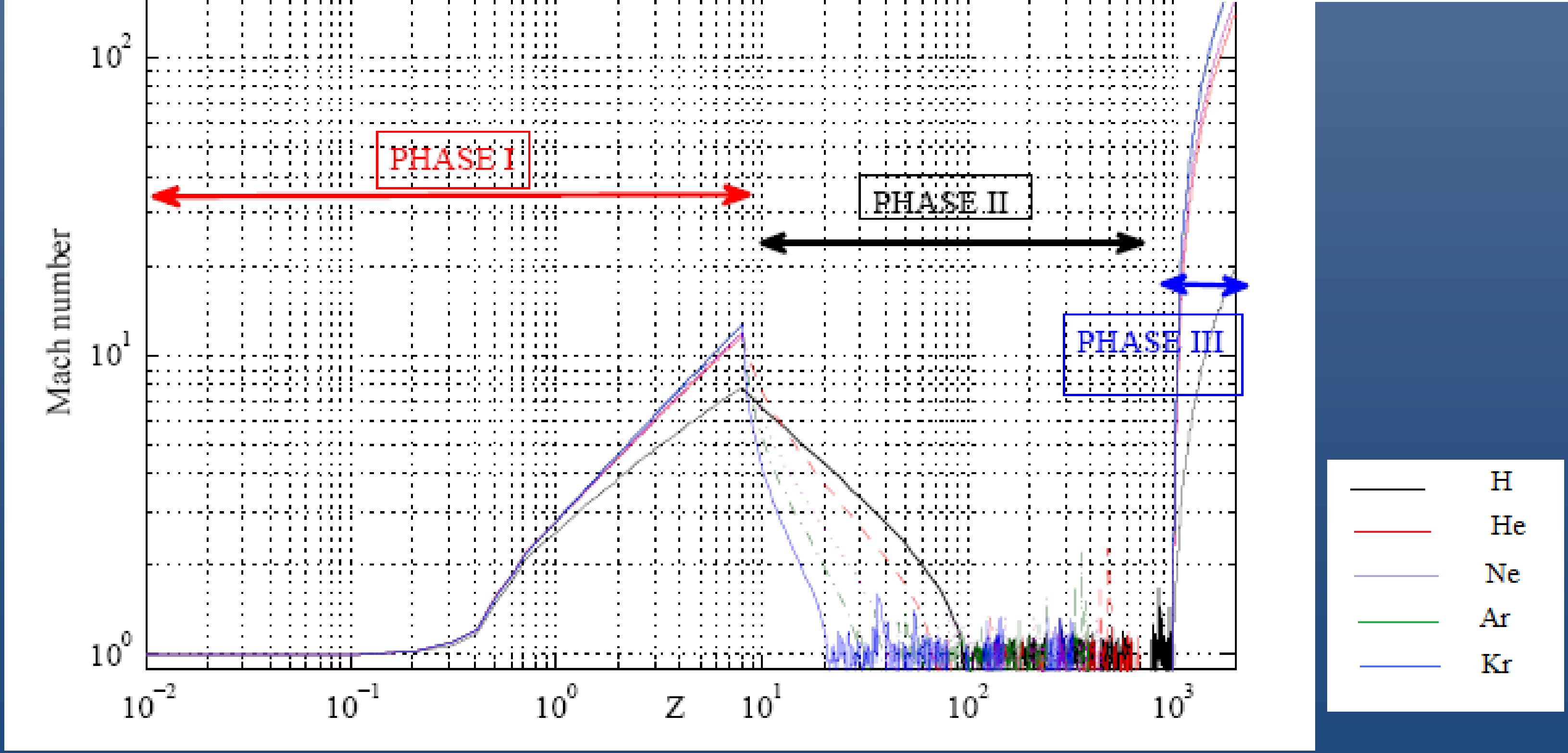
- Friction factor dependence on the flow judged to be turbulent or laminar according to Re number value (Re=ρ*VD*/μ).
- For Re>12000 → turbulent flow $\frac{l}{\sqrt{f}} = -2log(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}})$
- For Re<1200→ laminar flow $f = \frac{64}{Re}$
- For 1200<Re<12000 → transitional regime flow $\frac{l}{\sqrt{f}} = 2log\frac{Re\sqrt{f}}{2.51}$

# Numerical results for H, He, Ne, Ar and Kr

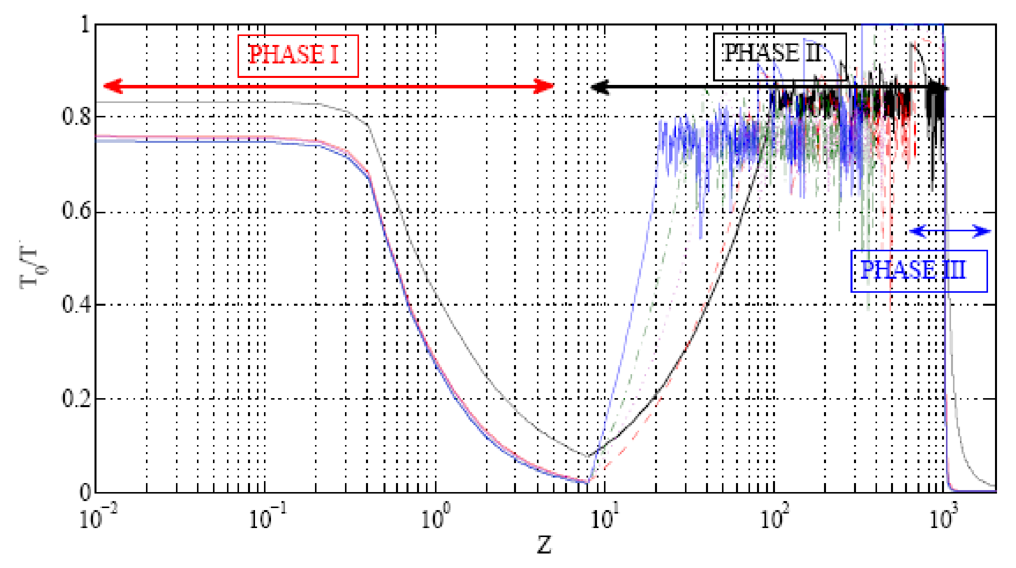
## Phase III is a free expanding jet case similar to phase I

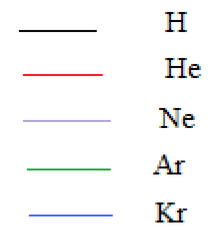
- Free gas jet expansion is characterized by the polynomial fit and
- The propagation in ducts is characterized by *f* and Re

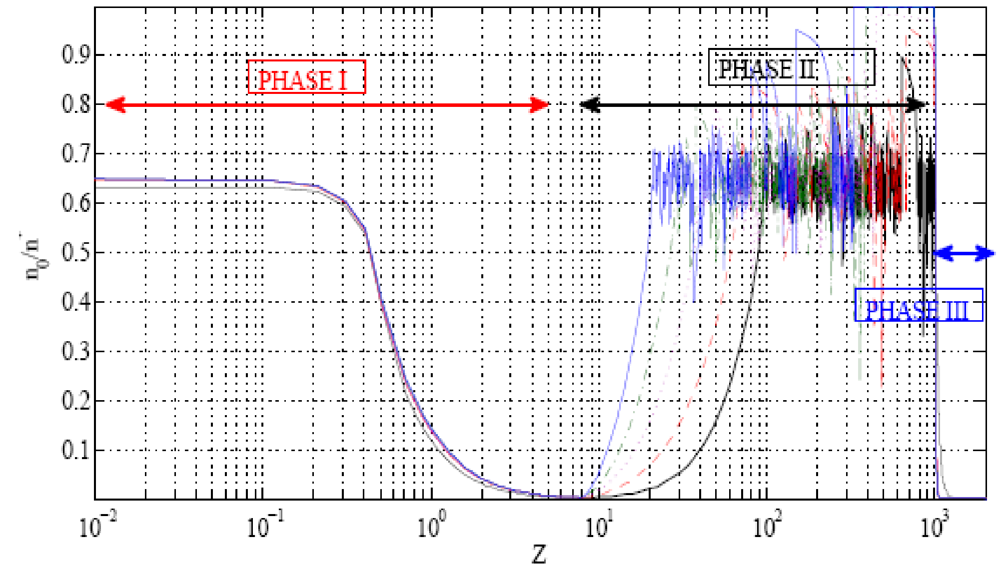




# Numerical results for H, He, Ne, Ar and Kr gases







# Conclusion I: Gas jet propagation in vacuum and in ducts

Using the polynomial fit to obtain the Mach number

1. Getting all the jet parameters as a function of the distance to the nozzle

2. The propagation in ducts is solved with the friction coefficient f obtained from the adequate formulas depending on the flow dynamics.

# Gas interaction with Plasma (phase IV):

# The Particle Balance equation

$$\partial_t n + \nabla.(n\vec{v}) = S$$

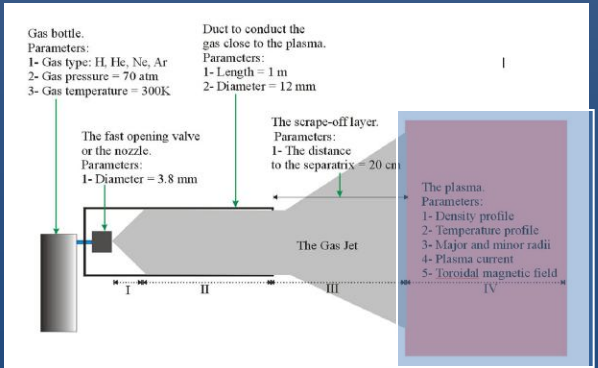
## Gas jet OFF

- Particle radial transport
- The “internal sources”

Continuous fuelling

Wall-particle interaction

NBI



## Gas jet ON

- Particle radial transport
- The “internal sources”

+

- Ionization
  - (II) $e^- + A \rightarrow A^+ + 2e^-$
  - (RI) $h\nu + A \rightarrow A^+ + e^-$
- Recombination
  - (3B.R) $2e^- + A^+ \rightarrow A + e^-$
  - (RR) $e^- + A^+ \rightarrow A + h\nu$
- Charge exchange → $A + B^- \rightarrow B + A^-$

# Particle Conservation Equation: Gas jet off

- The gas particles dynamics obey the following continuity equation:

$$\partial_t n + \nabla.(n\vec{v}) = S$$

- *S* is the particle source or/and sink term.
- Each quantity is set equal to its average and fluctuating value

$$n = n_0 + \tilde{n}$$

$$\vec{v} = \vec{v}_0 + \tilde{\vec{v}}$$

where

$$\langle \tilde{n} \rangle = \langle \tilde{\vec{v}} \rangle = 0$$

- Gas jet off, the plasma is in steady state, $\partial_t n=0$ *and let* $S=S_{in}$
- The continuity equation becomes

$$\partial_t n_0 + \partial_t \tilde{n} + \nabla.[(n_0\vec{v}_0) + (\tilde{n}\tilde{\vec{v}}) + (\tilde{n}\vec{v}_0) + (n_0\tilde{\vec{v}})] = S_{in}$$

$$\Big\downarrow \text{Time} \quad \text{Averaging}$$

$$\nabla.[\underbrace{(n_0\vec{v}_0)}_{①} + \underbrace{\langle \tilde{n}\tilde{\vec{v}} \rangle}_{②}] = S_{in}$$

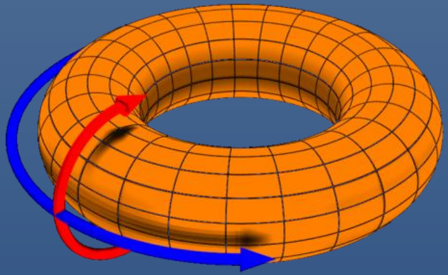
# Particle Conservation Equation: Gas jet off

①

$$\nabla.(n_0\vec{v}_0) = \frac{\partial_r(r n_0 v_{0r})}{r} + \frac{\partial_\theta(n_0 v_{0\theta})}{r} + \partial_\phi(n_0 v_{0\phi})$$

- $v_{0r} = 0$ (no radial expansion of the plasma).
- $v_{0\theta}$ and $v_{0\,\varphi}$ are assumed to have constant values independent of $\theta$ and $\varphi$ respectively.
- $v_{0\theta}$ and $v_{0\varphi}$ are input parameters (~1 &10 km/s)

$$\partial_\theta(v_{0\theta}) = \partial_\phi(v_{0\phi}) = 0.$$



- $n_0$ depends only on $r$, (no $\theta$ or $\varphi$ dependence).
- For the gas jet off case:

$$\boxed{\nabla.(n_0\vec{v}_0) = 0}$$

①

# Particle Conservation Equation: The turbulent term

- We write the particle flux as a function of $C$, the cross correlation coefficient between the velocity and the density.

$$\langle \tilde{n}\tilde{v}_r \rangle = C(\underbrace{\langle \tilde{n}^2 \rangle}_{2a}.\underbrace{\langle \tilde{v}_r^2 \rangle}_{2b})^{\frac{1}{2}} \tag{2}$$

$$\boxed{\frac{(\langle \tilde{n}^2 \rangle)^{\frac{1}{2}}}{n_0} = I_c + I_e(r/a)^{\xi}} \tag{2a}$$

**Obtained from the experiment** where $I_c$ and $I_e$ are turbulent fluctuation levels at plasma core and edge and $\xi$ is about 8.

**Assuming adiabatic electrons**

$$\frac{\tilde{n}}{n_0} = \frac{\tilde{\Phi}}{\Phi_0}.$$

**Assuming that velocity is dominated by ExB**

$$v_r = E_\theta B_\phi = -\frac{B}{r}\partial_\theta \Phi$$

$$\boxed{\langle \tilde{v}_r^2 \rangle = \frac{2\pi B^2 \Phi_0^2}{r^2 l^2} \langle \frac{\tilde{n}^2}{n_0^2} \rangle} \tag{2b}$$

# The final form of the internal source and the turbulent diffusion coefficient

$$\frac{(\langle\tilde{n}^2\rangle)^{\frac{1}{2}}}{n_0} = I_c + I_e(r/a)^{\xi}$$

$$\boxed{S_{in} = \nabla[\langle\tilde{n}.\tilde{\vec{v}}\rangle]} \longrightarrow \langle\tilde{n}\tilde{\vec{v}}_r\rangle = C(\langle\tilde{n}^2\rangle.\langle\tilde{v}_r^2\rangle)^{\frac{1}{2}}$$

$$\langle\tilde{v}_r^2\rangle = \frac{2\pi B^2\Phi_0^2}{r^2 l^2}\langle\frac{\tilde{n}^2}{n_0^2}\rangle$$

Using Fick's Law, we also obtain the expression of the turbulent diffusion coefficient as a function of the plasma parameters

$$\boxed{-D\partial_r n_0 = \frac{(2\pi)^{(1/2)} C B \Phi_0}{rl}(\frac{\delta n}{n_0})^2 n_0}$$

# Particle Conservation Equation: Gas jet on

$$\partial_t n_0 + \nabla(n_0\vec{v}_0) + \nabla(\tilde{n}\tilde{\vec{v}}) = S_{in} + S_{ext}$$

① ② ③ ④ ⑤

①

- $\partial n/\partial t$ is not equal to 0 since gas is being input into the device
- $n$ is no longer $r$ dependent only but $(r,\theta,\varphi)$-dependent .

②

$$\nabla(n_0\vec{v}_0) = n_0(\partial_r v_{0r} + \frac{1}{r}\partial_\theta v_{0\theta} + \partial_\phi v_{0\phi}) + v_{0r}\partial_r n_0 + \frac{v_{0\theta}}{r}\partial_\theta n_0 + v_{0\phi}\partial_\phi n_0$$

$v_{0r}$ is equal to zero

$$\nabla(n_0\vec{v}_0) = \frac{1}{r}\partial_\theta(n_0 v_{0\theta}) + \partial_\phi(n_0 v_{0\phi})$$

②

# Particle Conservation Equation: Turbulence contribution

③
$$\langle \nabla.(\vec{\tilde{n}\tilde{v}}) \rangle = \frac{1}{r}\partial_r \langle r\tilde{n}\tilde{v}_r \rangle + \frac{1}{r}\partial_\theta \langle \tilde{n}\tilde{v}_\theta \rangle + \partial_\phi \langle \tilde{n}\tilde{v}_\phi \rangle$$

- Particles being well bound along the magnetic field lines $\tilde{v}_\phi = 0.$

- <u>ASSUMPTION:</u> turbulence are isotropic in the ($r$,$\theta$) plane $\langle \tilde{n}\tilde{v}_r \rangle = \langle \tilde{n}\tilde{v}_\theta \rangle$

$$\nabla.(\langle \tilde{\vec{nv}} \rangle) = (\frac{1}{r} + \partial_r + \frac{\partial_\theta}{r})\langle \tilde{n}\tilde{v}_r \rangle$$

③

$$\boxed{\langle \tilde{n}\tilde{v}_r \rangle = -D\partial_r n_0 = \frac{(2\pi)^{(1/2)} C B \Phi_0}{rl}(\frac{\delta n}{n_0})^2 n_0}$$

- The diffusion coefficient is ($r$,$\theta$,$\phi$)-dependent since $n_0$ and $\Phi_0$ are ($r$,θ,$\phi$) dependent

- ④ is obtained previously when the gas jet is OFF

- ⑤ The ionization and recombination rates have analytical expressions

# Conclusion II: The Particle density conservation

1- For the gas jet OFF case: we used the fact of a stationary density profile to find the so-called internal sources and push the discussion further to find the expression of the particle diffusion coefficient.

2- For the gas jet ON: we have obtained all of the terms that should allow us to simulate the behavior of the density profile for a given temperature profile. In addition we can investigate the new expression of the diffusion coefficient that is $(r,\theta,\phi)$-dependent.

# Electron Heat equation: gas jet off

$$\frac{3}{2}n_e\partial_t T_e + \frac{3}{2}n_e\vec{v}_e.\nabla T_e = -\nabla.\vec{q}_e + Q_e$$

1 2 3 4

1 For the gas jet off, $\partial_t T_e = 0$

2 $\vec{v}_e.\nabla T_e = 0$

4

$$Q_e = Q_{OH} + Q_{e,i} + Q_{e,I} - Q_{e,n} - Q_{rad}.$$

$$Q_{e,n} = -n_e n_0 E_i \sigma_i$$

$$Q_\Omega = 2.8 \times 10^{-9}\frac{I^2}{a^4 T_e^{3/2}}$$

$$Q_{e,i} = -Q_{i,e} = \frac{3m_e n_e}{m_i \tau_e}(T_e - T_i)$$

$$Q_{rad} = Q_{Br} + Q_{rec} + Q_{line}$$

$$Q_{RR} = 4.1 \times 10^{-46} n_e n_Z T_e^{3/2} Z^6$$

$$Q_{line} = 1.8 \times 10^{-44} n_e n_Z T_e^{1/2} Z^4$$

$$Q_{Br} = 1.69 \times 10^{-26} n_e T_e^{1/2} \Sigma_i [Z^2 n_i]$$

25

# Electron Heat equation: Heat Flux Vector

3 $$\nabla.\vec{q}_e = \nabla.\vec{q}_e^{\,0} + \nabla.\vec{q}_e^{\,turb}$$

3a 3b

3a

## Frictional heat flux

$$\vec{q}_e^{\,u} = n_e T_e\left(0.71\vec{u}_\parallel + \frac{3}{2w_{ce}\tau_e}\hat{\phi}\times\vec{u}\right)$$

↓

$$\boxed{\nabla.\vec{q}_e^{\,u} = \partial_\phi q_e^{\phi} = \partial_\phi(0.71 n_e(r) T_e(r) u_\phi) = 0}$$

## Thermal heat flux

$$\vec{q}_e^{\,T} = \frac{n_e T_e \tau_e}{m_e}\left(-3.16\nabla_\parallel T_e - \frac{4.66}{w_{ce}^2\tau_e^2}\nabla_\perp T_e - \frac{5}{2w_{ce}\tau_e}\hat{\phi}\times\nabla T_e\right)$$

↓

$$\boxed{\nabla.\vec{q}_e^{\,T} = \frac{-4.66}{m_e w_{ce}^2 \tau_e r}\partial_r(r n_e T_e \partial_r T_e)}$$

3a

26

# Electron Heat equation: Including turbulence contribution

3b

$$\vec{q}^{\,turb} = \vec{q}_{\perp}^{\,turb} = q_r^{turb}\hat{r} + q_\theta^{turb}\hat{\theta}$$

$$q_\theta^{turb} = T_0\langle\tilde{n}\tilde{v}_\theta\rangle + \cancel{v_{0\theta}\langle\tilde{n}\tilde{T}\rangle} + n_0\langle\tilde{T}\tilde{v}_\theta\rangle$$

$$q_r^{turb} = \underbrace{T_0\langle\tilde{n}\tilde{v}_r\rangle}_{\text{Turbulent particle flux}} + \cancel{v_{0r}\langle\tilde{n}\tilde{T}\rangle} + \underbrace{n_0\langle\tilde{T}\tilde{v}_r\rangle}_{\langle\tilde{T}\tilde{v}_r\rangle = \frac{\kappa(r)}{n_0}\partial_r T_0}$$

$$\boxed{q_r^{turb} = \Gamma_r T_0 + \kappa(r)\partial_r T_0}$$

3b

- The gas jet OFF case, yields the expression of κ(*r*) according to the heat equation

$$\boxed{\partial_r(\kappa(r)\partial_r T_0) = Q_e - \partial_r q_{0r} - \partial_r(\Gamma_r T_0)}$$

27

# Electron Heat equation: gas jet ON

$$\boxed{\frac{3}{2}n_e\partial_t T_e + \frac{3}{2}n_e\vec{v}_e.\nabla T_e = -\nabla.\vec{q}_e + Q_e}$$

① ② ③ ④

① $\partial_t T_e \neq 0$

② $$\frac{3}{2}n_e\vec{v}_e.\nabla T_e = \frac{3}{2}n_e\left(\frac{v_{e\theta}}{r}\partial_\theta T_e + v_{e\phi}\partial_\phi T_e\right)$$

③ $$\nabla.\vec{q}_e = \nabla.\vec{q}_e^{\,0} + \nabla.\vec{q}_e^{\,turb} \quad \begin{cases} \nabla.\vec{q}_e^{\,0} = \frac{v_{0\theta}}{r}\partial_\theta(n_0T_0) + v_{0\phi}\partial_\phi(n_0T_0) \\ q_r^{turb} = T_0\Gamma_r + \kappa(r,\theta,\varphi)\partial_r T_0 \\ q_\theta^{turb} = T_0\Gamma_r + \kappa(r,\theta,\varphi)\partial_r T_0 \end{cases}$$

④ $Q_e$ is determined from the expressions of plasma heat losses and gains by ionization, recombination and radiation

# Conclusion III: The Electron Heat equation with the gas jet ON

- From steady state when the gas jet is OFF, we obtained the expression of κ as a function of the plasma parameters, namely $n$, $T$ and $\Gamma_r$.

- This equation is then used in the gas jet ON case after obtaining all the terms in the heat balance equation.

# General Conclusion I

- Some of the Major assumptions:
  - Turbulence is isotropic in the ($r$,θ)-plane
  - No dependence on θ and ϕ when the gas jet was OFF
  - Adiabatic electrons with velocity dominated by **E**x**B**

- We used Experimental-simulations results to
  - Determine the behavior of the jet just before interaction with the plasma
  - Obtain the density fluctuations profile

- Input parameters: $C$, $v_\theta$ and $v_\phi$

# General Conclusion II

- The jet properties were obtained as a function of the experimental setup configuration, e.g. gas bottle properties, duct(s) properties, SOL properties etc.

- When the gas jet is OFF, we got
  1. The expression of the internal sources and the diffusion coefficient as a function of the plasma properties
  2. The expression of the heat diffusion coefficient as a function of the plasma properties

- When the gas jet is ON, we obtained
  - The full equation for the particle conservation
  - The full equation for electron heat conservation
  - This includes among other the following physical phenomena: Turbulence, average gradients, ionization, recombination, ohmic heating, internal particle sources, radiation

# Future Work

- Write down the ion heat equation and repeat the same procedure;
- Include a study of the jet temperature variation after this one has reached the plasma.
- Study of the plasma sheath that appears near the jet and study the nature of convective electrons and ions motion in this region.
- Investigation of the multi-ionization process in order to write a generalized code capable of dealing with the great number of ionization and charge exchange reactions.
- Write down the code to simulate the equations and obtain numerical results mainly characterizing the plasma properties and the jet penetration.
- Compare the results to the experiment.

# Continuum Vs. Molecular Flows

- Continuum flow region presents high collision frequency responsible of maintaining equilibrium in both parallel and perpendicular directions to the jet axis.
- Molecular flow region:

  collisionless flow region where particles mean free path is in the same order or even greater than the expansion length.
- Separation of the two regions occurs at “Mach Disk” surface located at
- For fusion plasmas this distance is about 4 times the nozzle diameter;

  so basically we are working in the continuum flow region.

$$\frac{Z_M}{d} = 0.67\sqrt{\frac{P_0}{P_b}}$$